

## MONAURAL AND BINAURAL SPEECH INTELLIGIBILITY AND THE STEREOPHONIC EFFECT BASED UPON TEMPORAL CUES.\*†

J. DONALD HARRIS, Ph.D.,  
Groton, Conn.

Three important aspects of binaural hearing, namely: directionality, the "squelching" of reverberations, and markedly increased speech intelligibility, were all mentioned in anecdotal fashion by Koenig<sup>23</sup> on the basis of some observations he made with an artificial head, two microphones, and two earphones. A Y-cord arrangement, with one microphone feeding two earphones, or the outputs from two microphones merged and fed to two diotic phones, gave none of these three effects. Two other physicists, Knudsen<sup>20</sup> and Watson,<sup>33</sup> had reported improved intelligibility with binaural hearing. In these three laboratory pilot studies, the improvement of the binaural over the monaural condition was said to be quite apparent; but since no data were actually published, the force of the remarks in these three abstracts has been pretty well ignored, and no exact repetition of their apparatus and conditions has been attempted.

Of course, the question whether two ears are better than one has been settled at one level by the consumer of home audiosystems. Wherever the sound source is not a point, as with a single voice or instrument, a preference for stereo is clear. Likewise in the field of hearing aids, a large fraction of users are willing to bear the double burden of expense and discomfort to achieve dichotic representation.<sup>7,22</sup>

I remember clearly Koenig's talk, have had many personal episodes of temporary monaural deafness from one cause or another on a voluntary or involuntary basis, and have often lectured on the advantages of binaural hearing.<sup>10</sup> It comes,

\*The opinions expressed are not necessarily the official views of the Navy Department.

†From the U.S.N. Medical Research Laboratory, Groton, Conn.

therefore, as something of a shock to find Jerger and Dirks<sup>16</sup> speaking of the supposed superiority of binaural hearing aids as an "enigma." Indeed, in reviewing the experimental literature one is certainly struck with the lack of dramatic improvement provided by dichotic listening.<sup>6,13,17,24,27,34</sup> Could it be that the physicists cited, and the many clinicians who recommend binaural aids<sup>1,2,3,5,12,14,21,30,31</sup> were wrong? Could our Creator have simply hung a second ear on our heads purely as a mechanical safety factor in a chancy world?

One is of course prepared for quite good performance at many auditory tasks by one ear alone. There is little reason to suppose, for example, that speech intelligibility in noise, when both are coming from a point source directly ahead, would be improved in the binaural condition, just as one can read a sign straight ahead about as well with one eye as with two. Also the single ear is certainly capable of assigning some directional and distance value to a point source. There are, I conclude, some situations where one could hardly expect a second ear to aid and abet perception in real space. This thought led me to re-examine especially those experiments which demonstrated little or no benefit from dichotic listening. Could it be that some part of the reason for the small benefit was that situations had not been used in which a second ear could in fact be reasonably expected to increase communications efficiency? An analogous situation had been met with in monaural hearing aids, where the usual very easy tasks do not well differentiate among models.<sup>11</sup>

Allow me to apologize for recalling some details of these experiments with which the reader is probably familiar. Black and Hast<sup>4</sup> asked a talker to speak into two microphones placed as a six-inch-sided equilateral triangle with the mouth. Each mike was led to a separate recording channel, in phase in both channels, mixed with noise and fed to one or two earphones to American listeners with normal ears or with mild hearing loss, at various S/N ratios. Using the second ear had no effect; but note from the geometry of the situation that the signal as well as the noise was practically identical in the two earphones. The true virtue of binaural hearing can be expected to operate only when differences of phase, amplitude, and/or timing exist in the two earphones. This experi-

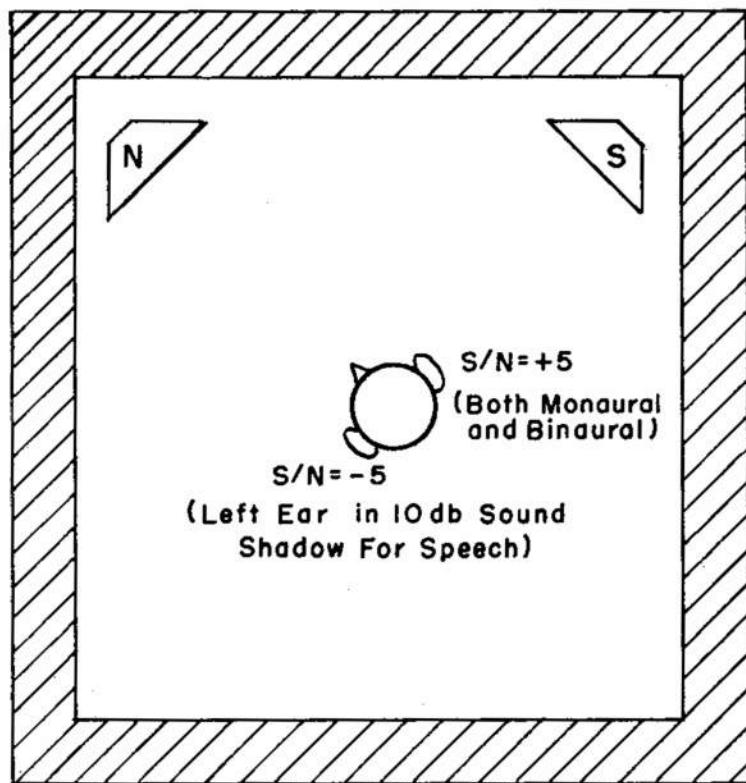


Fig. 1. Shows that when the head is free to move to attain maximum S/N ratio in the right ear, the left ear can hardly contribute importantly to binaural intelligibility.

ment is most like the Y-cord arrangement used by the physicists and specifically rejected by them as not showing an improvement over the monaural condition.

In a repetition of a study by Belzile and Markle<sup>1</sup> who had found a binaural advantage of 10 db S/N, Jerger and Dirks<sup>16</sup> failed to find any advantage; but if one thinks for a moment about the geometry of the Jerger and Dirks situation, the results are not surprising. In both the monaural and binaural conditions the aids were mounted in the vicinity of the pinna, and it is expressly stated that the head was free to move. When the speech comes from the right, what is more natural than to move the head so that the loudspeaker delivering

the speech looks directly into the right ear. In this case the head is turned to look directly at the noise loudspeaker so that noise is coming from the  $0^\circ$  azimuth; but in the binaural situation also, the head will be turned to a favorable position with respect to the speech loudspeaker, and the S/N ratio in the right ear will be exactly the same as in the monaural condition, thus the only difference between monaural/binaural will be what happens in the *left* ear. Now to the left ear the speech comes at an angle of  $135^\circ$  from the line looking into the ear canal—that is, attenuated effectively by the full shadow of the head, while the noise comes to the left ear at an angle of only  $0^\circ$  azimuth—that is, with almost no attenuation. Now the sound shadow of the whole head upon an ear creates about 10 db attenuation for speech threshold; thus, if the S/N ratio at the right ear is +5 for the binaural situation, it may be as poor as -5 for the left ear. In such a situation, one need not expect the left ear to contribute significantly to the monaural performance of the right ear (Fig. 1).

The contribution of Malles<sup>26</sup> to this problem cannot well be evaluated since he did not specify whether the head was free to move, though one would guess this to be the case; but unfortunately, he did not specify whether the speech was always fed to the side of the head wearing the hearing aid. If so, as was probably the case, his data can be interpreted to mean that adding a second ear in his unilateral loss patients did in fact cause an average improvement of about 20 per cent PB intelligibility at two S/N ratios; but because of the indefinite sound shadow of the head, one cannot state exactly what his S/N ratios were at the two ears.

If the head be not free to move, as in Wright and Carthart's<sup>34</sup> arrangement with an artificial head, or if the monaural aid be worn on the body where the sound shadow of the head cannot operate, the considerations are of course changed. In the case of the body-worn aid the monaural intelligibility should be worse than the head-worn, since the head cannot protect against the noise. In this case the binaural condition should be improved by the 10 db amount of the head's sound shadow—which is exactly what Belzile and Markle found. We do not have enough information about the attenuation of speech by the head's shadow to make an exact prediction of

the amount of binaural gain, but it is certain that the S/N ratio in the right ear will be the same for both binaural and monaural, and that a relatively unfavorable S/N ratio will exist in the left ear, which would in all likelihood have little or no effect if added; I, therefore, predict little improvement when the binaural situation is elaborated upon the head-worn monaural aid with no head movement permitted. Actually, Wright and Carhart<sup>34</sup> found that their *maximum* improvement was only 8 per cent (a rise from 21 to 29 per cent PB-in-noise intelligibility) when to a monaural aid on a dummy head was added a second aid in the same geometry as Belzile and Markle had used.

As a result of such reasoning, it was no surprise to me to read that Jerger, Carhart, and Dirks<sup>17</sup> found only a small improvement, and in only one of their dichotic listening tasks, when a single aid was moved from the body to the temple. It would seem that the subjects somehow did not take full advantage of the possibility of partially shadowing out the noise by moving their heads, but if not, then the binaural advantage should have been as apparent in their data, though it was not, as it was in that of Belzile and Markle. I am, therefore, driven to conclude that Jerger and Dirks are correct in speaking of these and similar data as an enigma.

Surely the enigma is not wrapped in an ineluctable mystery. There must be some way to settle, perhaps once and for all, whether binaural aids are in fact worth their weight.

It occurred to me that it should be possible to avoid the troublesome questions of head shadows and head movements by utilizing the stereophonic effect in designing the sound sources for monaural/binaural comparison. Here, with two loudspeakers placed symmetric to the midline, and with head movements minimized, all signals and noises enter the ear canals equal in all respects except for the specific differences in timing and S/N ratios built into the stimulus tapes.

I describe here one of the experiments completed in this laboratory, utilizing three 15-inch triaxial loudspeakers in an echo-free room to create the so-called "cocktail party," or, as I prefer to call it, the Box Social Effect, of several simultaneous talkers. The loudspeakers were placed in 45° steps

along a circle of 12 ft. radius, all facing two Western Electric 640AA microphones in the center of the circle. The microphones were separated from each other by 12 inches with no baffle between, so that the inputs to the Ampex 300-2C tape recorder differed only in the temporal cueing. My idea was to keep the situation and its interpretation as simple and unambiguous as possible. On a later occasion I expect to use our artificial head to secure the dichotic intensity effects which should appertain to the real-life situation.

The stereophonic arrangement described here is reminiscent of that of Pollack and Pickett,<sup>29</sup> who found a reliable improvement of 20 per cent and more in intelligibility for binaural as against monaural hearing. Their arrangement, however, was stereophonic only in the signal, not in the background; whereas the signal voice was split and led to the two channels of the tape recorder for diotic earphone presentation (the so-called "Y-cord"), the background voices later appearing on the two channels had been recorded previously and separately on single channels. The right ear of the listener, for example, never heard any of the background voices on the left channel, and the background material, therefore, is correctly described by the authors as "voice babble" rather than an example of true stereophony.

In our arrangement the midline loudspeaker was fed by a tape playback upon which had been recorded 100 sentences of PAL Test #8 and to which the patient could respond by multiple-choice. The talker was a man with less than average articulation clarity. The left and right loudspeakers were fed by a second and third tape recorder, respectively, from a woman reading from "Gentlemen Prefer Blondes," and a man reading an amusing eulogy to the Model T, "Farewell, My Lovely."

In some preliminary trials, tapes from the midline questioner and either of the background voices were played and adjusted one at a time in level until at the position of the microphones, each background voice just masked the questioner. The background voices were then turned down 10 db, and played continuously while the midline speaker presented the sentences. It was thought that the resultant two-

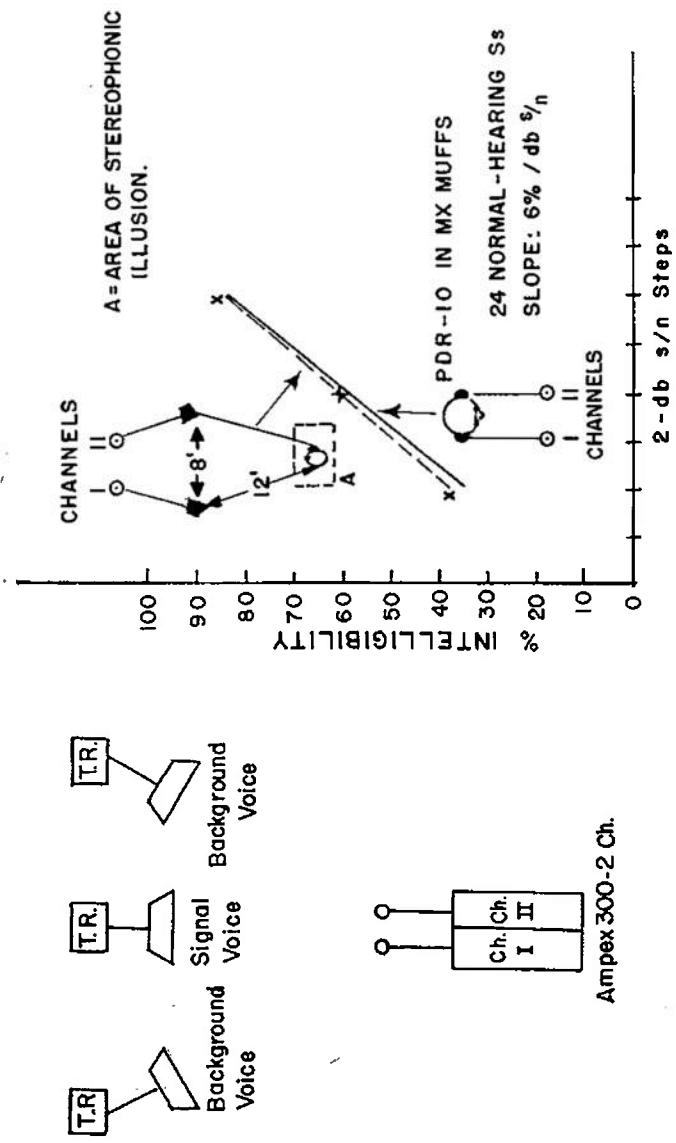


Fig. 2. Shows the comparability of loudspeaker and earphone presentations of the stereophonic illusion.

channel tape would be fairly easy for all listeners. The talker tapes were then rewound, the background voices raised each 2 db, and all 100 sentences recorded again, and so on, for a total range of 12 db S/N, until stimulus tapes were created both too easy and too difficult for normal-hearing listeners.

When these stimulus tapes were played back in a second echo-free room from two loudspeakers eight feet apart and facing a point 12 feet away, a subject could at that point sit comfortably in a chair and experience the authentic stereophonic illusion, with his head oriented in the midline, but positioned anywhere in a cube roughly 1 x 1 yard on a side. The questions appeared to emanate from a concealed loudspeaker straight ahead; of the background voices, the woman's appeared to come from the left and the man's from the right.

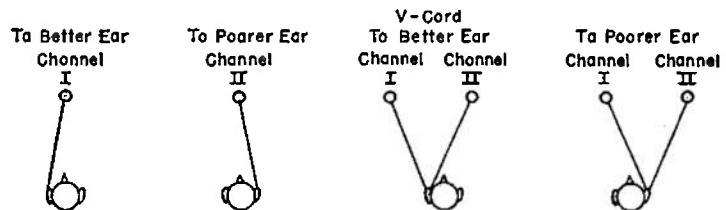
I turned these tapes and the playback gear and room over to my esteemed colleague, Mr. C. K. Myers, who scheduled 24 normal-hearing subjects in a first comparison of loudspeakers vs. earphones at equal S/N ratio for binaural listening.

The results as shown in Fig. 2 were adequate to convince me that it is possible to abandon the loudspeaker administration and to utilize the great advantage to be gained for theory by being able to lead the two taped channels to earphones. Not only can the channels in the earphone situation be adjusted for equal loudness by the patient with asymmetric loss, but the Y-cord condition and several other connections from channels to ears can be accomplished in modes not possible with loudspeakers.

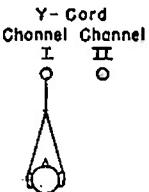
At this point I felt that the correct tool had been devised with which to assess possible advantages of binaural hearing for speech intelligibility. Among the specific questions I hoped to throw light on with this line of attack were:

1. In the normal-hearing person, is there in fact a Principle of Binaural S/N Gain, when correct conditions are provided for its emergence? If so, in what monaural defects can amplification, as with a single hearing aid, restore enough binaural hearing to improve intelligibility furnished by the better ear?

## MONAURAL MODES



## DIOTIC MODE



## DICHOTIC MODES

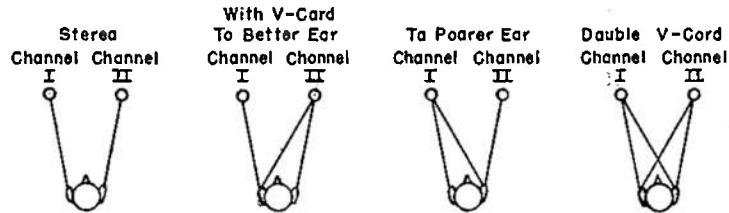


Fig. 3. Modes of presenting to the ears information stored on tape by stereophonic recording technique.

2. Is there a Principle of Redundancy, such that a second channel added to a single ear improves intelligibility?
3. Is there a Principle of Blurring, such that an ear's performance is less efficient if presented simultaneously with cues from two separate and non-congruent points in space?
4. Is there a Principle of Degradation, such that the information in a second channel, amplified and led to a defective ear will, by the characteristics of that ear, be degraded and be a positive detriment to the other ear?
5. Are there ways to connect the two channels to the two

ears superior to the usual stereo earphone patching, ways which utilize perhaps the Principle of Redundancy as well as the Principle of Binaural S/N Gain?

In order to bear upon these questions, I specified nine listening modes, as diagrammed in Fig. 3; however, it was not possible to submit any patient to more than four modes, since it necessitated a minimum of 25 sentences to establish an intelligibility score for any one mode. We had recourse, therefore, to matched-group sampling. Eighty-nine normal-hearing

TABLE I.  
Comparison of Modes for Normal Listeners—All Data at Constant S/N Ratio.  
Entry: Per Cent Intelligibility.

Group	Monotic	Dichotic; Stereo	Diotic; Y-Cord	Monotic; V-Cord	Dichotic; with V-Cord to One Ear	Dichotic; with Double V-Cord
A	Mn S.D. S.E. N: 34	23.7 13.2 2.3	50.5 11.7 2.0	29.6 10.8 1.9		
B	Mn S.D. S.E. N: 55	26.7 12.5 1.7		33.3 11.0 1.5	48.2 16.2 2.2	39.9 13.0 1.7
A+B	Mn S.D. S.E. N: 89	25.5 12.7 1.9				

individuals in two groups were all given a Monaural Mode, the mean score between groups differing by the statistically insignificant amount of 3 per cent. One group was then given two other modes, the other group three different modes. The results are in Table I.

A number of positive statements can now be made:

1. The Principle of Binaural S/N Gain seems to be operating. This conclusion can be based upon two comparisons:

a. In all three modes with dichotic stimulation, statistically significant gains are found of the order of 15-25 per cent over the monaural, but this is not true with the Y-cord Mode; for the latter mode, adding a second ear (but without dichotic conditions) has an insignificant effect of 4 per cent (29.6-25.5 per cent).

b. The V-cord Mode, where a second channel is added but furnished to the *same* ear, is inferior (by up to 17 per cent) to those three modes where *both* ears are receiving some sort of dichotic information and can operate in a truly binaural fashion.

2. A Principle of Redundancy exists. When the slightly different information in the second channel was added (V-cord Mode), a significant improvement resulted of about 8 per cent (33.3-25.5 per cent) as compared with the Monaural Mode for that ear.

3. A Principle of Blurring may exist. When the two ears are receiving directly the two channels (Stereo Mode), maximum intelligibility is reached; if then one blurs the information in one ear by leading to it a channel recorded from any other point in space (Dichotic, with V-cord to one ear), no real loss occurs. But if *both* ears receive blurred information (Dichotic, with Double V-cord), a significant drop of 10.6 per cent (50.5-39.9 per cent) occurs.

To check on this important point, another group of 16 normal listeners was given the Stereo Mode and the Dichotic Mode with Double V-cord. At a certain constant S/N ratio, means of  $65.6 \pm 1.8$  per cent and  $67.0 \pm 2.5$  per cent were obtained, indicating no blurring in this group.

4. The Principle of Redundancy, which can lead to an accretion of intelligibility, and the Principle of Blurring, which can lead to a decrease in intelligibility, may exist simultaneously, the Principle of Redundancy being the stronger. They are found together at the most uncomplicated mode in the V-cord arrangement, where the algebraic resultant is a reliable gain over the Monaural Mode for our subjects of about 7.8 per cent.

The V-cord Mode has been remarked upon by several workers who have expressed themselves as favoring that mode over the monaural. It can be achieved in the monaurally deaf by having two hearing aids on the head as Fowler,<sup>8</sup> Friedlander,<sup>9</sup> and Wüllstein and Wigand<sup>35</sup> suggested, the microphone on the deaf side connected either to the ac receiver on the good side or to a bc receiver on the deaf side.

These clinical observations, so far as they go, corroborate the qualitative observations in the laboratory of Watson<sup>22</sup> and Koenig,<sup>23</sup> on the superiority of the V-cord Mode for speech intelligibility in the normal ear as compared with the monaural. It was said by Mouzon<sup>24</sup> and by Fowler<sup>8</sup> that the directionality of the human voice is improved if the two circuits to the same ear have different frequency-response characteristics. Whether this difference improves intelligibility is open to experimental attack.

TABLE II.  
Comparison of Modes for Defective Listeners—All Data At Same Constant S/N  
Ratio as Table I.  
Entry: Per Cent Intelligibility.

Group	Monotic			Y-Cord	Stereo	Double V-Cord
	Better Ear	Poorer Ear	Better to Poorer			
C	Mn	29.1	14.6	45.2	47.6	
	S.D.	11.9	16.5	13.7	9.3	
	S.E.	3.0	4.1	3.4	2.3	
	N: 16					
D	Mn		58.6	31.8	51.4	63.0
	S.D.		13.2	14.8	20.2	9.8
	S.E.		2.9	3.3	4.6	2.2
	N: 20					
C+D	Mn				49.7	
	S.D.				15.3	
	S.E.				3.6	
	N: 36					

I conclude as a result of these data on normal ears that the Principles of Binaural S/N Gain, of Redundancy, and perhaps of Blurring, are established. It remains to be determined whether with partially defective ears the same or similar trends appear. Thirty-six patients with asymmetrical audiograms from Mr. Myers' clinic were examined by him, the loudness in the poorer ear always equated to that in the better by individual balancing. Results are in Table II.

For the Stereo Mode, at which direct comparison can be made between the two subgroups of 20 and 16 patients, the difference between means is not reliable at even the very lax 10 per cent level of confidence. I conclude, therefore, that it is justified to compare modes across as well as within subgroups. On this assumption, I believe it is correct to say that

the patients' data corroborate the trends from the normal listeners, with a few important extensions and additions:

1. Adding a second ear in the Stereo Mode reliably improves intelligibility by about 25 per cent, an effect quite similar to that with normals, but this even when the second (poorer) ear is *by itself* markedly inferior to the normal ear in the Monaural Mode (about 15 per cent worse). Apparently the inherent defective nature of the second ear need not by the Principle of Degradation sharply reduce its dichotic contribution when its loudness loss is artificially overcome. Furthermore, all two-ear modes are superior, by up to 33.9 per cent, to the Monaural (better ear) Mode. The Principle of Binaural S/N Gain is thus corroborated in the clinical material.

2. When to the second (poorer) ear is fed the identical information fed to the first (better) ear (Y-cord Mode), the same negligible increase (3 per cent) is found as with normals. There is thus certainly no reason to consider the diotic mode further as a practical matter (see also Bibl. 32); however, theoretically this means that the Principle of Binaural S/N Gain in the Stereo Mode does not depend upon the second ear *as such* (by furnishing *duplicate* cues for intelligibility) but upon the *additional* temporal cues contributed by the other ear, cues which can be melded with those from the first ear in the brainstem to create the stereophonic illusion.

An explanation is needed for the improvement found by Pollack and Pickett,<sup>29</sup> whose mode as described above was diotic (Y-cord) for the signal, with entirely uncorrelated background material in the two ears. This situation never occurs in nature, and cannot be duplicated with binaural hearing aids, so that its practical importance is negligible. In their situation the background voices could hardly be "squelched" (as Koenig<sup>23</sup> put it) by the nervous system operating upon the slight phase and intensity differences in the inputs at the two ears as in true stereophony; and the Y-cord for the signal voice is known not to increase intelligibility by any appreciable amount. The explanation lies in the prior experiment of Licklider,<sup>25</sup> who presented speech by Y-cord, and noise at the two ears either correlated or uncorrelated. When the noise was

correlated (both signal and noise homophasic; recall that this was Black and Hast's<sup>4</sup> situation), intelligibility was 18 per cent, but when the noise was rendered uncorrelated, the intelligibility rose to 27.4 per cent. It was suggested that in the homophasic condition the interaural interactions for signal and for noise were of similar types, with central masking thereby possible.

3. The Principle of Redundancy is demonstrated with especial force in the clinical material (see the two V-cord modes). The gain for the V-cord Mode (better ear) over the Monaural Mode (better ear) is 29.5 per cent while for the poorer ear the gain is 30.6 per cent.

4. The Principle of Blurring, if indeed it exists, cannot be detected in the clinical material. Whereas the change from Stereo to Dichotic (Double V-cord) Mode caused a loss of 10.6 per cent in the normal listener, interpreted by me as a blurring effect in consequence of the two ears each receiving information from non-congruent points in space, in the clinical material on the other hand an *increase* of 13.3 per cent is found (63.0-49.7).

5. The Principle of Degradation, that a defective ear will cause a decrease in intelligibility if loudness loss is artificially overcome (Stereo Mode) can be established in this material. That it exists can be inferred from the fact that the Stereo Mode is inferior to the Monaural (V-cord to better ear) Mode, which latter has the redundancy feature of the Stereo Mode but lacks the contribution of the poorer ear. The difference, in the direction predicted by the Principle of Degradation, is 8.9 per cent, significant at the 5 per cent level of confidence.

6. The 13.3 per cent improvement of the Dichotic (Double V-cord) Mode over the Stereo Mode is sufficient to warrant investigation in the clinic of binaural hearing aids arranged in this fashion, with wires across the head connecting the two microphones to the receivers. Of course, in our laboratory arrangement of the Dichotic (Double V-cord) Mode, isolating transformers and attenuators were used to create equal loudness for all four inputs separately, an apparatus requirement difficult to duplicate with a hearing aid array; but with fairly

symmetrical bilateral audiometric losses this refinement may prove unnecessary.

A final check was run on the generality in a free field of the gain to be expected, on the basis of these data, from the joint operation of the Principles of Redundancy and of Binaural S/N Gain. This was arranged by exposing a group of normal listeners to the two-loudspeaker array described above, responding with and without a V51-R plug in one ear. With the particular S/N ratio used, these procedures gave means of  $47.1 \pm 2.5$  per cent for the monaural and  $65.2 \pm 2.2$  per cent for the binaural, an improvement of 18.1 per cent for the binaural mode, significant at better than the 1 per cent level of confidence.

In order to render this demonstration of the superiority of binaural listening more convincing, the above Monaural Mode was taken with both loudspeakers operating. This corresponds most closely to the earphone Monaural (V-cord) Mode, which has been shown in Table I to be by the Principle of Redundancy about 8 per cent superior to the Monaural Mode for normals. Had we turned off the second loudspeaker, the Binaural Mode of the previous paragraph might have exceeded the Monaural by a value somewhat larger than 18.1 per cent.

As a consequence of these observations, it seems correct to say that both normal and defective listeners profit significantly from the Dichotic modes, both in the free field and under earphones. The improvement, on the basis of temporal cues exclusively, amounts at a minimum for defective ears to 20.6 per cent (Stereo Mode minus Monaural [Better Ear] Mode), and at a maximum to 33.9 per cent (Double V-cord minus Monaural [Better Ear] Mode). At the observed exchange of 6 per cent intelligibility per db S/N ratio (Fig. 1), these percentages convert to gains of about 3.5 to 5.5 db S/N ratio. Such gains, while not spectacular, can nevertheless be substantial if the patient is thereby enabled to enter situations or communicate in ways previously denied him.

Of the three advantages of binaural listening listed by Koenig,<sup>23</sup> only increased intelligibility and the rapid inhibition of reverberation are involved in this study. For this purpose,

we extend his observation on reverberation to include any background sound. The improvement with binaural hearing of the third advantage, directionally, has been well established.<sup>3,6,14,15,18,19,32</sup> But it is quite possible that increased intelligibility and the "squelching" of reverberation are not two separate aspects, but effect and cause. The reduction of background noise by neural processing would create an improved effective S/N ratio which would eventuate in improved intelligibility. From the calculations in the previous paragraph, I would estimate that the gain in S/N ratio due to binaural hearing is of the order of 5 db.

#### SUMMARY AND CONCLUSIONS.

A review is presented of experiments on the purported gain in intelligibility for the binaural over the monaural condition. It is concluded that in some previous experiments uncontrolled head movements, the sound shadow of the head, and/or presenting both speech and noise from the same loudspeaker had rendered the test uninterpretable or even insensitive to any possible binaural improvement.

A test was devised by using three separate voices to two microphones and recording on two-channel tape (the Box Social Effect). Presenting this tape to two loudspeakers in a free field or to two earphones gives the stereophonic effect in both cases, and comparable improvements in intelligibility for two ears vs. one ear. Nine modes of patching channels to earphones were then devised, using isolating networks and attenuators for loudness balancing between ears: four monotic modes (one channel to better ear; one channel to poorer ear; both channels to better ear; both channels to poorer ear); one diotic mode (one channel to both ears); and four dichotic modes (each channel to a separate ear; one channel to poorer ear; both channels to better ear, one channel to better ear; both channels to poorer ear, both channels to both ears).

By comparisons among modes on 89 normal and 36 asymmetrically defective subjects, the following principles were established:

- a. The Principle of Binaural S/N Gain: on a truly appropriate test, the improvement in intelligibility of dichotic over

monotic modes is of the order of 25-33 per cent (about + 4 to + 5 db S/N ratio).

b. The Principle of Redundancy: a significant gain of 8-30 per cent is achieved by adding a second channel to the monotic ear, whether that ear is normal or defective.

c. A possible though minor Principle of Blurring: there is a slight indication that adding a second channel from a non-congruent point in space may somewhat blur intelligibility; but this tendency would usually be overcome by the stronger Principle of Redundancy.

d. The Principle of Degradation: the contribution of a defective ear in the Stereo Mode decreases binaural intelligibility as compared with leading two channels to the better ear.

Some or all of these four principles may coexist; intelligibility will be the algebraic resultant of the direction and strength of the tendencies operating.

In a direct free field test with normal listeners of the Principle of Binaural S/N Gain, an improvement of about 20 per cent intelligibility resulted for both ears as against one ear (the unplugged ear listened to both channels and had consequently the advantage of the Principle of Redundancy). This 20 per cent increase is taken to be the lower limit for the gain to be expected with a binaural hearing aid array.

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